

# Semi-Inclusive DIS and Transversity

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**Abstract.** A review is presented of some aspects of semi-inclusive deeply inelastic scattering and transversity. In particular, the role of  $k_T$ -dependent and higher-twist (or multi-parton) distributions in generating single-spin asymmetries is discussed.

## INTRODUCTION

A large part of the material presented here is gleaned from [1, 2], where the coverage is more complete. Therefore, much credit and thanks go to my two collaborators: Enzo Barone and Alessandro Drago. Further (less condensed and more complete) conference reviews may also be found in other proceedings [3, 4]. Finally, the space available forces a limited choice of topics and there are, unfortunately, many I cannot even mention.

By way of motivation for the interest, let me recall that transversity is the last piece in the partonic jig-saw puzzle of the hadron. A number of experiments aim at its study: HERMES, COMPASS and the RHIC spin programme. And while the QCD theory describing transversity is now solid, transverse-spin effects are notoriously surprising; consider, *e.g.*, the unexpectedly large single-spin asymmetries (SSA's).

Transversity then is the third and final leading-twist ( $\tau = 2$ ) partonic distribution function. Now, it is important to distinguish between partonic distributions:  $q(x)$ ,  $\Delta q(x)$ ,  $\Delta_T q(x)$  *etc.* and DIS structure functions:  $F_1$ ,  $F_2$ ,  $g_1$ ,  $g_2$  *etc.* In both the unpolarised and helicity-dependent cases at leading twist there is a simple correspondence between the two: DIS structure functions are little more than weighted sums of partonic distributions (or densities). However, in the transverse-spin case, firstly, there is no DIS transversity structure function and, secondly,  $g_2$  does not correspond to a partonic density.

The parton-model description provides a simple probabilistic view of hadron structure (herein I shall use  $f_1$ ,  $g_1$  and  $h_1$  generically):

$f_1(x)$  or  $q(x)$  represent the probability of finding a given parton type with light-cone momentum fraction  $x$  inside a given parent hadron;

$g_1(x)$  or  $\Delta q(x)$  the same but weighted by parton helicity relative to parent helicity;

$h_1(x)$  or  $\Delta_T q(x)$  weighted by transverse-spin projection relative to parent transverse-spin direction.

Note, however,  $h_1(x)$  does not measure quark transverse polarisation;  $g_2$  has this role.

Turning now to SSA's, they generically reflect correlations of the form  $\vec{s} \cdot (\vec{p} \wedge \vec{k})$ , where  $\vec{s}$  is a particle spin vector,  $\vec{p}$  and  $\vec{k}$  are initial/final particle/jet momenta; for example,  $\vec{s}$  might be a target polarisation vector (transverse),  $\vec{p}$  a beam direction and  $\vec{k}$  a final-state particle direction. Thus, spins involved in SSA's are typically transverse (however, there are exceptions). Transforming the spin basis from transversity to helicity such an asymmetry takes on the schematic form, using  $|\uparrow / \downarrow\rangle = \frac{1}{\sqrt{2}}[|+\rangle \pm i|-\rangle]$ ,

$$\mathcal{A}_N \sim \frac{\langle \uparrow \uparrow | \uparrow \rangle - \langle \downarrow \downarrow | \downarrow \rangle}{\langle \uparrow \uparrow | \uparrow \rangle + \langle \downarrow \downarrow | \downarrow \rangle} \sim \frac{2\text{Im}\langle + | - \rangle}{\langle ++ \rangle + \langle -- \rangle}. \quad (1)$$

The appearance of both  $|+\rangle$  and  $|-\rangle$  in the numerator indicates a spin-flip amplitude. Indeed, interference between a spin-flip and a non-flip amplitude, with a relative phase difference, is necessary. It was realised early on [5] that in the Born approximation and massless (or high-energy) limit a gauge theory, such as QCD, cannot furnish either requirement: fermion helicity is conserved and tree diagrams are real. This naturally led to the claim [5] that “... *observation of significant polarizations in the above reactions would contradict either QCD or its applicability.*”

Now, although large experimental asymmetries were found, QCD survived! A way out was discovered [6] by considering the three-parton correlators involved in  $g_2$ : the relevant mass scale when considering helicity flip is not the quark mass but a hadronic mass; and the pseudo two-loop nature of the diagrams leads to an imaginary part in certain regions of partonic phase space. However, it took some time before progress was made and the richness of the available structure was fully exploited (see, *e.g.*, [7]).

## A BRIEF HISTORY OF TRANSVERSITY

Quark *transversity* (the concept though not the term<sup>1</sup>) was introduced by Ralston and Soper [9] in the Drell–Yan (DY) process. An important clarification of transversity, the role of chirally-odd parton distributions and the general twist classification was provided by Jaffe and Ji in [10]<sup>2</sup>, see Table 1. As twist runs from 2 to 4, the number of “bad” light-cone components runs from 0 to 2.

The leading-order (LO) anomalous dimensions for transversity were first calculated very early on in [12], which went unnoticed, and later re-calculated in [13]. They were also calculated (as part of the  $g_2$  evolution) in [14–17]. The next-to-leading-order (NLO) DY coefficient functions were calculated in [18, 19] while the NLO anomalous dimensions were calculated in [20–22]. The effects of evolution have been studied by many authors—for more details and a general review see, *e.g.*, [1].

**Table 1.** The twist classification (up to  $\tau = 4$ ) for the various parton distributions, including spin dependence (both transverse and longitudinal).

	twist	2	3	4
unpolarised		$f_1$	$e$	$f_4$
longitudinal		$g_1$	$h_L$	$g_3$
transverse		$h_1$	$g_T$	$h_3$

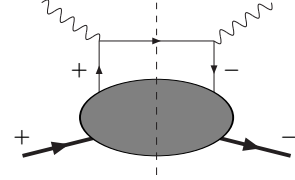
<sup>1</sup> For very early use of the term *transversity*, see [8].

<sup>2</sup> The term *transversity*, following [11], was also suggested to distinguish it from transverse spin.

## TRANSVERSE-SPIN BASICS

Transversity is one of three twist-two structures:

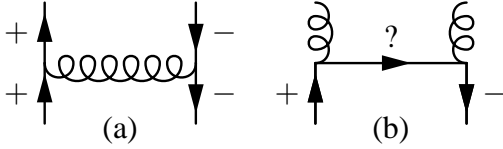
$$\begin{aligned} q(x) &= \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS | \bar{\psi}(0) \gamma^+ \psi(0, \xi^-, \vec{0}_\perp) | PS \rangle, \\ \Delta q(x) &= \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS | \bar{\psi}(0) \gamma^+ \gamma_5 \psi(0, \xi^-, \vec{0}_\perp) | PS \rangle, \\ \Delta_T q(x) &= \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS | \bar{\psi}(0) \gamma^+ \gamma^1 \gamma_5 \psi(0, \xi^-, \vec{0}_\perp) | PS \rangle. \end{aligned}$$



**Figure 1.** Chirality-flip DIS diagram forbidden by helicity conservation.

Here the  $\gamma_5$  matrix signals spin dependence while the extra  $\gamma^1$  matrix in  $\Delta_T q(x)$  signals chirality flip; this last precludes transversity contributions in DIS, see Fig. 1.

QCD and electroweak vertices conserve quark chirality. Thus, charged-current interactions exclude transversity, since only a single chirality interacts. Note though that chirality flip is not a problem if the quarks connect to different hadrons (as in DY). However, a caveat to measuring transversity in DY is that the azimuth of the lepton pair be left unintegrated. The same observations lead to another important consequence: the LO QCD evolution of transversity is of the non-singlet type, see Fig. 2.



**Figure 2.** (a) Evolution kernel for transversity. (b) Disallowed gluon-fermion mixing kernel.

## TRANSVERSITY: MODELS AND QCD

Having opposite charge-conjugation properties,  $\Delta q$  and  $\Delta_T q$  are not simply related. Decomposing  $\Delta q$  as  $\Delta q^{\text{NS}} + \Delta q^{\text{S}}$ , one might imagine  $\Delta_T q \simeq \Delta q^{\text{NS}}$ . In the non-relativistic quark model this is the case. However, in a relativistic model the lower quark wavefunction components spoil the identity and, e.g., the MIT bag gives [10]:

$$\Delta q^{\text{NS}} = c \int r^2 dr (f^2 - \frac{1}{3}g^2) \quad \text{while} \quad \Delta_T q = c \int r^2 dr (f^2 + \frac{1}{3}g^2), \quad (3)$$

where  $f$ ,  $g$  (the upper, lower components) contribute differently due to the extra  $\gamma_0$ .

By considering hadron-parton amplitudes Soffer [23] derived an intriguing bound:  $|\Delta_T q(x)| \leq q_+(x)$  or  $2|\Delta_T q(x)| \leq q(x) + \Delta q(x)$ . In QCD the question arises as to the effects of evolution on this bound [24]: its maintenance has been checked explicitly to LO in [25], to NLO in [26] and discussed on more general grounds in [27]; experimental verification thus becomes an important test.

The LO (non-singlet) DGLAP quark-quark splitting functions are

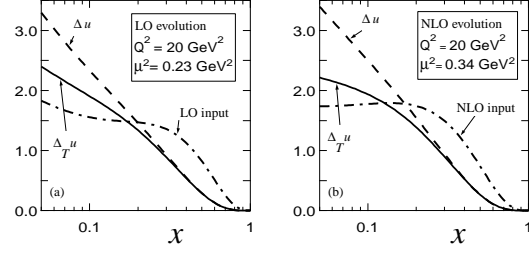
$$\Delta P_{qq}^{(0)}(x) = P_{qq}^{(0)}(x) = C_F \left[ \frac{1+x^2}{1-x} \right]_+ \quad (\text{due to helicity conservation}), \quad (4a)$$

$$\Delta_T P_{qq}^{(0)}(x) = P_{qq}^{(0)}(x) - C_F(1-x). \quad (4b)$$

Thus, for both  $P_{qq}^{(0)}$  and  $\Delta P_{qq}^{(0)}$  the first moments vanish (leading to conservation laws and sum rules). The same is not true for  $\Delta_T P_{qq}$  and so, there are no transversity sum rules.

The importance of this difference has been studied both at LO and NLO. The sign indicates that quark transverse polarisation decreases, as compared to longitudinal polarisation. This is both bad news, since transversity effects therefore die at very high energies (though only very slowly), and good news, since evolution effects are stronger and therefore more measurable (*i.e.*, they are good for testing QCD).

The chirally-odd nature of transversity means that at least two hadrons are needed to probe transversity:  $p^\uparrow p^\uparrow \rightarrow \mu^+ \mu^- X$  [9, 28];  $ep^\uparrow \rightarrow e' \pi X$  [29–31];  $pp^\uparrow \rightarrow \Lambda^\uparrow X$  [32];  $ep^\uparrow \rightarrow \Lambda^\uparrow X$  [33];  $ep^\uparrow \rightarrow e' \pi^+ \pi^- X$  [30, 34, 35] *etc.* There are thus two basic categories: double- and single-spin asymmetries. I shall now examine the latter more closely.



**Figure 3.** The  $Q^2$ -evolution of  $\Delta_T u(x, Q^2)$  and  $\Delta u(x, Q^2)$  at (a) LO and (b) NLO, from [20].

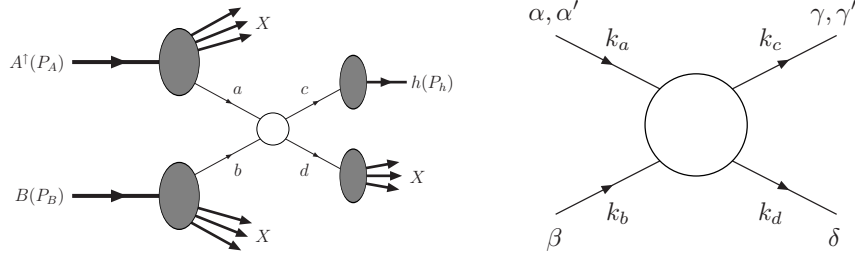
## SINGLE-SPIN ASYMMETRIES

SSA's can be generated in various ways: higher-twist,  $k_T$ -dependent distribution or fragmentation functions; or interference and vector-meson fragmentation functions. Consider single-hadron production with a transversely polarised beam or target:

$$A^\uparrow(P_A) + B(P_B) \rightarrow h(P_h) + X, \quad (5)$$

where  $A$  is transversely polarised and the unpolarised (or spinless) hadron  $h$  is produced at large transverse momentum; PQCD is thus applicable. One measures the SSA:

$$\mathcal{A}_T^h = \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)}. \quad (6)$$



**Figure 4.** Left: a schematic representation of single-hadron production with a transversely polarised beam or target. Right: the hard partonic scattering amplitude  $\mathcal{M}_{\alpha\beta\gamma\delta}$  ( $\alpha \dots \delta$  are Dirac indices).

According to the factorisation theorem, the differential cross-section for semi-inclusive production may be written formally as

$$d\sigma = \sum_{abc} \sum_{\alpha\alpha'\gamma\gamma'} \rho_{\alpha'\alpha}^a f_a(x_a) \otimes f_b(x_b) \otimes d\hat{\sigma}_{\alpha\alpha'\gamma\gamma'} \otimes \mathcal{D}_{h/c}^{\gamma\gamma'}(z), \quad (7)$$

where  $f_a$  ( $f_b$ ) is the density of parton type  $a$  ( $b$ ) in hadron  $A$  ( $B$ ),  $\rho_{\alpha\alpha'}^a$  is the spin density matrix of parton  $a$ , and  $\mathcal{D}_{h/c}^{\gamma\gamma'}$  is the fragmentation matrix for parton  $c$  into final hadron  $h$ . The elementary cross-section is ( $\mathcal{M}_{\alpha\beta\gamma\delta}$  is the hard partonic scattering amplitude)

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{\alpha\alpha'\gamma\gamma'} = \frac{1}{2} \sum_{\beta} \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{\alpha\alpha'\beta\beta'\gamma\gamma'} = \frac{1}{16\pi s^2} \frac{1}{2} \sum_{\beta\delta} \mathcal{M}_{\alpha\beta\gamma\delta} \mathcal{M}_{\alpha'\beta'\gamma'\delta}^*. \quad (8)$$

The off-diagonal elements of  $\mathcal{D}_{h/c}^{\gamma\gamma'}$  vanish, *i.e.*,  $\mathcal{D}_{h/c}^{\gamma\gamma'} \propto \delta_{\gamma\gamma'}$  when the hadron produced is unpolarised. Helicity conservation then implies  $\alpha = \alpha'$ , thus precluding any dependence on the polarisation of hadron  $A$ . Either intrinsic quark transverse motion, or higher-twist effects can circumvent this conclusion.

Quark intrinsic transverse motion can generate SSA's in three different ways (always necessarily as  $T$ -odd effects):

1.  $\vec{k}_T$  in the final hadron  $h$  allows  $\mathcal{D}_{h/c}^{\gamma\gamma'}$  to be non-diagonal (fragmentation level).
2.  $\vec{k}_T$  in hadron  $A$  requires  $f_a(x_a)$  be replaced by  $\mathcal{P}_a(x_a, \vec{k}_T)$ , which may depend on the spin of  $A$  (distribution level).
3.  $\vec{k}_T'$  in hadron  $B$  requires  $f_b(x_b)$  be replaced by  $\mathcal{P}_b(x_b, \vec{k}_T')$ . The transverse spin of  $b$  in the unpolarised  $B$  may then couple to the transverse spin of  $a$  (distribution level).

The three mechanisms are: 1. Collins [29]; 2. Sivers [36]; and 3. an effect studied in by Boer in [37]. All such intrinsic- $\vec{k}_T$ ,  $-\vec{k}_T$ , or  $-\vec{k}_T'$  effects are  $T$ -odd; they require initial- or final-state interactions. Note that when quark transverse motion is included, the QCD factorisation theorem is not completely proven, but see recent work in [38].

The Collins mechanism exploits intrinsic quark motion inside the produced hadron  $h$ . Thus, assuming factorisation to be valid, the cross-section difference is

$$E_h \frac{d^3\sigma(\vec{S}_T)}{d^3\vec{P}_h} - E_h \frac{d^3\sigma(-\vec{S}_T)}{d^3\vec{P}_h} = -2|\vec{S}_T| \sum_{abc} \int dx_a \int dx_b \int d^2\vec{k}_T \frac{1}{\pi z} \times \Delta_T f_a(x_a) f_b(x_b) \Delta_{TT} \hat{\sigma}(x_a, x_b, \vec{k}_T) \Delta_T^0 D_{h/c}(z, \vec{k}_T^2), \quad (9)$$

where  $\Delta_{TT} \hat{\sigma}$  is a partonic spin-transfer differential cross-section difference (see, *e.g.*, [1]). The Sivers effect relies on  $T$ -odd  $k_T$ -dependent partonic distribution functions and predicts SSA's of the form

$$E_h \frac{d^3\sigma(\vec{S}_T)}{d^3\vec{P}_h} - E_h \frac{d^3\sigma(-\vec{S}_T)}{d^3\vec{P}_h} = |\vec{S}_T| \sum_{abc} \int dx_a \int dx_b \int d^2\vec{k}_T \frac{1}{\pi z} \times \Delta_0^T f_a(x_a, \vec{k}_T^2) f_b(x_b) \frac{d\hat{\sigma}(x_a, x_b, \vec{k}_T)}{d\hat{t}} D_{h/c}(z), \quad (10)$$

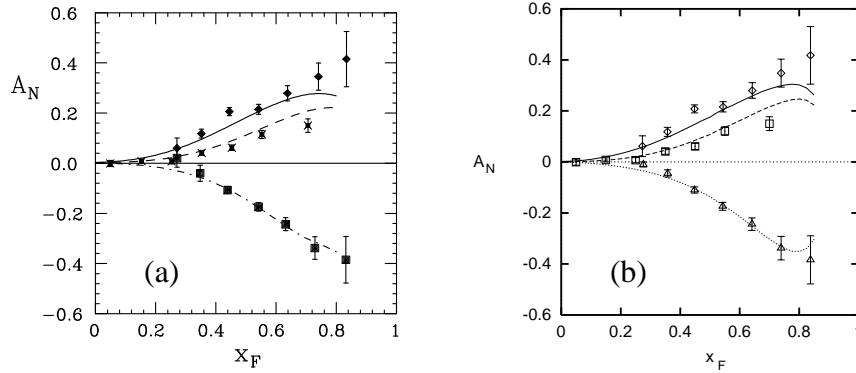
where  $\Delta_0^T f$  (related to  $f_{1T}^\perp$ ) is a  $T$ -odd distribution. Finally, the effect studied by Boer [37] gives rise to an asymmetry involving another  $T$ -odd  $k_T$ -dependent distribution  $\Delta_T^0 f$  (related to  $h_1^\perp$ ) and a partonic initial-spin correlation differential cross-section  $\Delta_{TT} \hat{\sigma}'$ :

$$E_h \frac{d^3 \sigma(\vec{S}_T)}{d^3 \vec{P}_h} - E_h \frac{d^3 \sigma(-\vec{S}_T)}{d^3 \vec{P}_h} = -2|\vec{S}_T| \sum_{abc} \int dx_a \int dx_b \int d^2 \vec{k}'_T \frac{1}{\pi z} \times \Delta_T f_a(x_a) \Delta_T^0 f_b(x_b, \vec{k}'_T^2) \Delta_{TT} \hat{\sigma}'(x_a, x_b, \vec{k}'_T) D_{h/c}(z). \quad (11)$$

It was shown in [39] that non-vanishing SSA's can also be obtained in PQCD by resorting to the gluonic poles present in higher-twist diagrams involving  $qqg$  correlators. Such asymmetries were evaluated in [7], where direct photon production was studied, and for single hadron production later in [40]. This program was extended to cover chirally-odd contributions in [41]. In the general case one has

$$d\sigma = \sum_{abc} \left\{ G_F^a(x_a, y_a) \otimes f_b(x_b) \otimes d\hat{\sigma} \otimes D_{h/c}(z) + \Delta_T f_a(x_a) \otimes E_F^b(x_b, y_b) \otimes d\hat{\sigma}' \otimes D_{h/c}(z) + \Delta_T f_a(x_a) \otimes f_b(x_b) \otimes d\hat{\sigma}'' \otimes D_{h/c}^{(3)}(z) \right\}. \quad (12)$$

The first term does *not* contain transversity and is the chirally-even mechanism studied in [40]; the second *does* contain transversity and is the chirally-odd contribution analysed in [41]; and the third contains transversity and a twist-3 fragmentation function  $D_{h/c}^{(3)}$ .



**Figure 5.** Single-spin asymmetries Assuming (a) only Siverson [42] and (b) only Collins [43] mechanisms.

Models inspired by the previous possible ( $k_T$ -dependent) contributions compare well to data in [42, 43]. Indeed, phenomenological fits based on either the Siverson or Collins mechanisms work equally well and are thus impossible to distinguish at present, see Fig. 5. The calculations based on three-parton correlators [7] are opaque, involving many diagrams, complex momentum flow, colour and spin structure. One sees that unfortunately the current knowledge at both the theoretical and experimental level do not permit a clear and concise description of these phenomena.

However, the twist-3 correlators obey constraining relations with  $k_T$ -dependent densities and they also exhibit a novel factorisation property. It is this simplification that I shall now describe in more detail. The twist-3 diagrams involving 3-parton correlators supply an imaginary part via a pole term [6] (spin-flip is implicit).

The  $i\varepsilon$  propagator prescription (for  $\bullet$  in Fig. 6), leads to an imaginary contribution for  $k^2 \rightarrow 0$ :

$$\frac{1}{k^2 \pm i\varepsilon} = \mathbb{P} \frac{1}{k^2} \mp i\pi\delta(k^2), \quad (13)$$

For a gluon, with momentum  $x_g p$ , inserted into an initial or final external line  $p'$ , one has  $k = p' - x_g p$ , and thus  $x_g \rightarrow 0$ . This can be shown systematically for all poles (gluon and fermion), *i.e.*, on all external legs with all possible insertions [44].

This still generates very complex structures; there are many possible insertions, with contributions of different sign and momentum dependence. The colour structure of the various diagrams is also very different. In all cases examined just one diagram dominates in the large- $N_c$  limit (see Fig. 6), *i.e.*, other insertions into external legs are suppressed by

$$\text{Pole Part} = -i\pi \frac{p' \cdot \xi}{p' \cdot p} \times \text{Diagram}$$

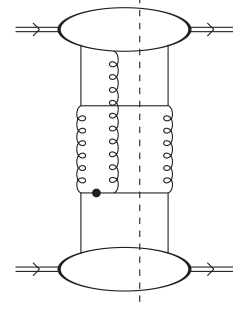
**Figure 7.** A graphical representation of the higher-twist pole-factorisation mechanism.

Assuming that similar simplifications can also be found for the  $k_T$ -dependence, then by relating the higher-twist to the  $k_T$ -dependent mechanisms via the equations of motion, unique predictions may be possible for azimuthal SSA's. A study along these lines has indeed already been made for DY in [45]; predictions were, however, found *not* to be unique there. The  $k_T$ -dependence and higher-twist connections have also been exploited in [46].

## SUMMARY AND CONCLUSIONS

Transversity is now considered equally important an aspect of nucleon structure as the other two leading-twist parton densities and a complete description of the nucleon requires its understanding. Theoretically, all the pieces of the PQCD puzzle (up to NLO) are in place and lattice calculations indicate transversity to be sizable. On the experimental side, unfortunately, there are as yet no real data. However, the future is promising and before long we shall start to harvest interesting results. The phenomenology, while not dissimilar to the other leading-twist structures, has interesting peculiarities: evolution is non-singlet (so analysis should be cleaner), spin-half objects can contain gluonic transversity but it is not accessible via the usual partonic hard-scattering processes (this should perhaps be examined) and there is no associated sum rule (thus QCD evolution is faster). This all suggests that transversity could, in principle, allow clean extraction of  $\alpha_s$  from the evolution fits to the scale violating  $Q^2$  variation (*cf.* unpolarised).

SSA's have progressed from having essentially no (PQCD) theory to almost too much! Hopefully, the multitude of mechanisms can be reduced to just a few simple terms: experiment can eliminate some possibilities if null results are obtained; relationships between three-parton correlators and  $k_T$ -dependent densities should show up equivalences between apparently different phenomenological models; while pole-factorisation and the large- $N_c$  limit can simplify calculations and allow a clear pattern to emerge.



**Figure 6.** Example of a dominant higher-twist diagram in the large- $N_c$  limit.

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